Assuring the Safety of Nuclear Power

Livermore's Fission Energy and Systems Safety Program is addressing the most important nuclear power issues for the federal government and, increasingly, foreign nations. The program's research is tied directly to each stage in the nuclear fuel cycle.

FEW areas of modern technology receive as much government—and public—scrutiny as nuclear power. With the goal of providing an independent authority to oversee the operation and licensing of civilian nuclear power plants, the federal government in 1972 formed the Nuclear Regulatory Commission (NRC). Since its inception, the NRC has relied upon national experts, including those at Lawrence Livermore, for independent, expert advice in virtually every aspect of nuclear power.

Indeed, the original group of Livermore nuclear power experts was named the NRC Program because it provided technical support for that government agency's regulations concerning nuclear systems. The Livermore program is now called the Fission Energy and Systems Safety Program (FESSP), but its goal remains the same, namely, to address the most important nuclear power issues for both the NRC and the Department of Energy (DOE), the nation's nuclear agencies.

Scope of the FESSP

The FESSP currently conducts more than 95 projects in 17 technical areas of nuclear energy. According to Mark Strauch, assistant deputy associate director for Energy Programs and deputy FESSP head, "All of our projects correspond to a part of the nuclear fuel cycle that begins when you dig uranium out of the ground and ends when you put the products back in the ground."

The Livermore program is unique because it was built around the nuclear fuel cycle (see box, p. 7). C. K. Chou, deputy associate director for Energy Programs and FESSP head, notes that Livermore's FESSP works on all aspects of the fuel cycle: mining; enrichment; power reactor operation; nuclear materials handling, storage, transportation, and waste management; repository development; nuclear facilities security; and regulatory reform. Such an umbrella organization, says Chou, fosters a broad perspective of nuclear power issues.

The program's activities have spun off to other national research programs at Lawrence Livermore, to Vice President Al Gore's office for using the power of electronic communication to make the federal government more efficient, and increasingly, to other countries for enhancing the safety of their national nuclear power programs (see box, p. 8).

The program taps the talents and expertise of many disciplines found at Livermore, including engineering; computer science; chemistry; geosciences, traditional environmental, health, and safety disciplines; safety analysis methodology; policy making; and safeguards and security. Besides their academic training, many FESSP people have practical experience in the nuclear industry.

One of the program's great strengths, its computer simulation codes for determining risks to nuclear safety systems, is derived from codes originally developed for Livermore's nuclear weapons development program. Indeed, all of the program's work benefits from a heritage of research on nuclear materials and processes dating from Lawrence Livermore's very beginning in 1952.

Addressing Public Concerns

Strauch notes that in providing about 20% of the nation's electrical needs, the 109 U.S. nuclear plants use processes and materials that are perceived by the public as extremely hazardous. In response to that concern, the nuclear industry has put into place safety systems comparable in complexity and integrity to those found on manned space flights. Assuring that these systems mitigate hazards requires an understanding of both external and internal threats. External threats include natural phenomena such as earthquakes, tornadoes, floods, and fires. Internal threats include everything inside the plant from a corroding pipe to a faulty instrument to human error.

The FESSP has long been involved in aspects of uranium mining and enrichment, the first two stages of the nuclear fuel cycle. The program has conducted studies of uranium tailings left over from mining uranium ore. It supports DOE's nuclear safety upgrade program at the United States Enrichment Corporation's (USEC) two enrichment plants that use gaseous diffusion technology.

FESSP experts are currently performing engineering and cost analyses for the selection of a long-term management strategy for the DOE's inventory of depleted uranium hexafluoride (UF_6). There now exist about 560,000 metric tons of depleted UF_6, left over from uranium enrichment activities. The results of the comprehensive analysis will assist DOE in evaluating the environmental impacts and costs of implementing management alternatives.

Once enriched fuel reaches reactors, it can be used only if structural, electrical, human, and safety systems are performing as designed. Over the past 20 years, the program has conducted a number of risk-assessment studies to support NRC regulations concerning reactor operation, ranging from the integrity of reactor coolant pipes to the software that controls critical systems.

The FESSP program has pioneered new approaches to determining risk (Figure 1) from many sources, but especially dangers posed by earthquakes. (For more information on risk assessment, see *Science & Technology Review*, August 1995, p. 16.) The Livermore staff conducted the first U.S. seismic probabilistic risk assessment for siting nuclear power plants from 1978 to 1985 using a new methodology called Probabilistic Risk Assessment (PRA) that is now used widely by the NRC and public utilities. The staff is currently helping the NRC to overhaul its seismic siting criteria for new nuclear power plants.

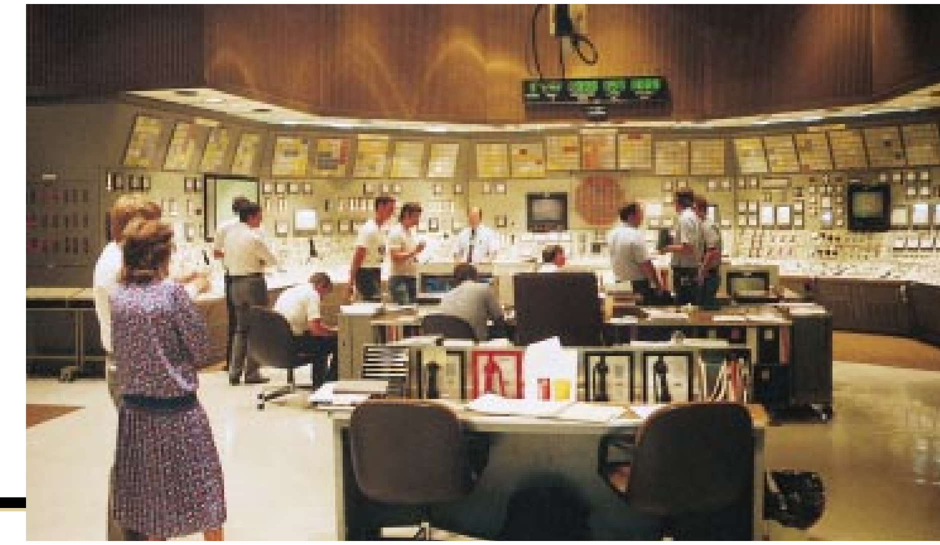


Figure 1. Control room of a nuclear power plant. Probabilistic risk assessment methodology from Lawrence Livermore is used by the Nuclear Regulatory Commission (NRC) and utility companies to evaluate risks in all stages of the nuclear fuel cycle.

According to FESSP engineer Jean Savy, “PRA forces the user to rationally analyze a plant’s components and their interactions in a systems framework. It reveals the weak links and calculates a scale of the relative likelihood of any component failing.”

In an effort to diminish internal threats, Livermore Livermore is working with NRC to set new industry safety standards for digital control of instruments and safety systems being introduced in many power plants. “We want to ensure that digital systems are doing exactly what they’re supposed to do,” says computer afety and reliability manager Gary Johnson. In particular, Johnson’s group works to ensure that the quality and diversity of software in redundant systems will minimize risk of common mode failures such as bugs in the software.

Fuel Storage and Transport

Risk analysis also comes into play to resolve issues that are related to storing and transporting spent nuclear fuels and other radioactive materials. FESSP experts have helped to determine the level of safety that must be provided when spent reactor fuel is transported to a nuclear waste facility. In the future, tens of thousands of spent nuclear fuel assemblies, now under temporary storage at power plants, will be transported to a federal repository for storage.

Shipment of spent fuel from U.S. commercial nuclear power plants, now occurring at a very low rate, is regulated by both the Department of Transportation and the NRC. The NRC evaluates and certifies the shipping casks, which are designed to protect the public from potential radiological hazard.

In one study for the NRC, the FESSP calculated the probable impact on shipping casks of 31 different truck accident scenarios and 24 different rail-accident scenarios. The safety analysis was based on extensive accident data and new computer analysis techniques developed at Livermore, and casks were field tested (Figure 2) (see *S&TR*, August 1995, pp. 18–19). In another study, FESSP staff reviewed several current cask designs for the NRC so that transporting spent fuel would be permitted to continue.

FESSP has developed an integrated software system called SCANS (Shipping Cask Analysis System), which the NRC uses to analyze the structural integrity of the storage casks under a series of normal operating loads and hypothetical accident loads. The software has been adapted for analyzing spent-fuel storage casks as well.

Currently, the program is reviewing DOE’s proposals for changing the NRC’s methods of evaluating the safety of a spent-fuel transport cask.

Safeguarding Data, Materials

One of the nuclear industry’s most important tasks is ensuring that proper security is in place at nuclear power plants and other key facilities. FESSP is supporting the DOE in meeting security requirements throughout the agency’s nuclear-related facilities.

The Argus security system, developed by Livermore’s Safeguards and Security program, is an interconnected, computer-based personnel access system that serves the Laboratory’s Livermore and Site 300 facilities. The DOE has selected Argus as the standard automated electronic-security technology for its entire complex. Argus installations offer an access control function to allow entry by authorized personnel to specific buildings and areas, an intrusion detection system to monitor rooms containing classified documents or special nuclear material, and a central console dispatch system to oversee operation of both the access control and intrusion detection system.

Figure 2. One-third-scale casks that will be used to transport spent nuclear fuel are impact-tested at Site 300. Data are used to refine the codes that predict the casks’ structural integrity.

FESSP people are providing Argus-type installations at DOE’s Pantex Plant in Texas, the Idaho Chemical Processing Plant, the Air Force National Test Facility, and the Rocky Flats Environmental Technology Site. They are also assisting in the conceptual design of installations at Los Alamos National Laboratory and Idaho National Engineering and Environmental Laboratory.

Data can be as precious as nuclear materials, and FESSP people are working to control access to data, enhance secure communications, and achieve cost efficiencies in the process. For example, the program has developed an upgrade to the systems used by the Office of Personnel Management and DOE to process some 30,000 security clearances and reinvestigations annually (see *S&TR*, August 1996, pp. 18–19).

As part of FESSP’s information security efforts, staff members have developed a strong capability in implementing so-called firewalls to protect information from unauthorized users. These information technology strengths were used to create the NRC’s RuleNet World Wide Web page to elicit public comments and help make the

The Nuclear Fuel Cycle

The nuclear fuel cycle consists of the activities associated with producing electricity from enriched uranium, beginning with the mining of uranium and ending with the disposal of spent fuel and nuclear waste. The cycle is typically described as comprising a “front end” (preparing nuclear fuel for reactor operation) and a “back end” (managing the spent nuclear fuel).

Front End

At uranium mills, uranium oxide is extracted from ore containing between 0.1 and 1% uranium. The mill product, uranium oxide, is called “yellowcake” and contains more than 60% uranium. The uranium oxide is prepared for enrichment by chemical conversion to uranium hexafluoride (UF_6), a solid at room temperature but a gas at a slightly higher temperature.

In light-water-moderated reactors that are used by the U.S. nuclear power industry, enrichment is required because natural uranium’s content of the fissile uranium-235 isotope (0.7%) is too low to sustain a nuclear chain reaction. The enrichment process boosts the concentration of uranium-235 to between 3.5% and 4.5%.

The gaseous diffusion enrichment process is currently used in the U.S. while gas centrifuge separation is employed in Europe. A third technology, AVLIS (atomic vapor laser isotope separation), is under advanced development by the United States Enrichment Corporation (USEC) at Lawrence Livermore. It uses 30% less uranium (and only 5% of the energy) than gaseous diffusion to produce a comparable amount of enriched product and does not require yellowcake to be converted to UF_6.

Currently, the enriched UF_6 is changed into pellets of ceramic uranium oxide that are sealed into corrosion-resistant tubes and placed in fuel assemblies. During reactor operation, the uranium 235-atoms fission, liberating heat, while the uranium-238 atoms absorb a free neutron and form uranium-239, which in turn decays to plutonium-239, a fissile isotope of plutonium.

The heat in the reactor core is carried away as steam, which passes to an electrical turbine generator for producing electricity. More than 40 million kilowatt-hours of electricity are produced from 1 ton of natural uranium, the equivalent of burning over 16,000 metric tons of black coal or 80,000 barrels of oil.

Back End

After its operating cycle (about 18 months), the reactor is shut down for refueling. The spent fuel rods are usually stored in water for both cooling and radiation shielding. Ultimately, the spent fuel will be transported for permanent disposal.

It is technically possible to extract the unused uranium and plutonium from spent nuclear fuel through chemical reprocessing and to recycle them as nuclear fuel. Currently both are done at plants in Europe with spent fuel from utilities in Europe and Japan. The U.S. has decided not to pursue the reprocessing option.

A current concern is the safe disposal and isolation of either spent fuel from reactors or, if reprocessing is done, wastes from reprocessing plants. Under the Nuclear Waste Policy Act of 1982, the U.S. Department of Energy has responsibility for the development of a national waste disposal system for spent nuclear fuel and high-level radioactive waste. Current plans call for the ultimate disposal of the wastes in solid form in deep, stable geological structures such as the proposed Yucca Mountain site in Nevada, but none is yet in operation.

regulatory process less burdensome. FESSP also helped to bring online the Vice President's Office of National Performance Review to communicate the federal government's latest efforts to make its operations more efficient.

The program also has established a Nuclear Systems Safety Center (NSSC) to serve as an online national resource for nuclear system information and analysis. The NSSC is linked via communications networks to the NRC, national laboratories, and other elements of the technical community.

A Home for Nuclear Waste

One of the greatest challenges facing DOE experts is determining the suitability of a potential underground site for the nation's first high-level nuclear-waste repository. By the year 2010, about 63,000 metric tons of nuclear waste from commercial nuclear power reactors and 7,000 metric tons of solidified nuclear waste from defense programs are slated for permanent disposal in an underground repository (see *S&TR,* April 1997, pp. 4–13).

Scientific studies are continuing in the evaluation of the suitability of the Yucca Mountain, Nevada, site as a potential long-term repository. Lawrence Livermore's contribution to the project is the design of the engineered barrier system that will ensure containment of the nuclear waste. For several years, FESSP has been evaluating the waste form, the performance of candidate waste package materials, and the geologic environment.

FESSP scientists are also developing conceptual models, computer codes, laboratory experiments, and field tests to demonstrate the validity of their "localized dryout" concept for positioning the repository tunnels and placement of the waste containers. This approach uses the heat from the waste containers to drive moisture away from the tunnel walls, thus potentially delaying any container corrosion for tens of thousands of years.

According to FESSP project leader Bill Clarke, two important Livermore facilities have opened recently. The first is a heavily instrumented, room-size block of rock adjacent to the proposed Yucca Mountain site. Instruments in this rock gather data on moisture, temperature, water geochemistry, corrosion of metal samples, gas pressure and vapor, acoustics, deformation, and rock stresses (see *S&TR*, March 1996, p. 14–15).

The second facility is a new corrosion-testing laboratory at Livermore that allows the investigation of modes of corrosion in candidate materials for the waste package (Figure 3). This facility contains several dozen large vessels, each measuring about 1 meter square and 2 meters high, in which investigators simulate possible environmental conditions at an underground repository.

FESSP expertise is also being tapped as part of a DOE-led effort to study the best ways to dispose of weapons-grade plutonium recovered from dismantled weapons or in existing inventories that will remain unused. The program is working on new container designs that would allow the handling of plutonium oxide for mixed-oxide fuel fabrication for nuclear power reactors. FESSP experts are also aiding a wider Livermore effort to study the viability of two plutonium disposition options: immobilization in either glass or ceramic and burial in a deep borehole. The program also is performing safeguards and security studies for each of these options (see *S&TR*, April 1997, pp. 4–13).

Strong Future

With more than 100 U.S. nuclear power plants producing electricity, nuclear waste management policies still under discussion, and many foreign nations' nuclear industries seeking assistance on safety issues, it seems clear that the federal government will continue to require astute, independent technical expertise. In that regard, Chou says that the program's paramount goal is to be

Livermore's Global Outreach to Enhance Nuclear Safety

Lawrence Livermore's Fission Energy and Systems Safety Program (FESSP) is involved in a host of international projects devoted to all aspects of the nuclear fuel cycle, but particularly to those concerned with enhanced reactor safety. FESSP experts are working with colleagues from Morocco, Britain, Australia, New Zealand, the Czech Republic, Japan, South Korea, Sweden, Spain, China, and nations of the Former Soviet Union.

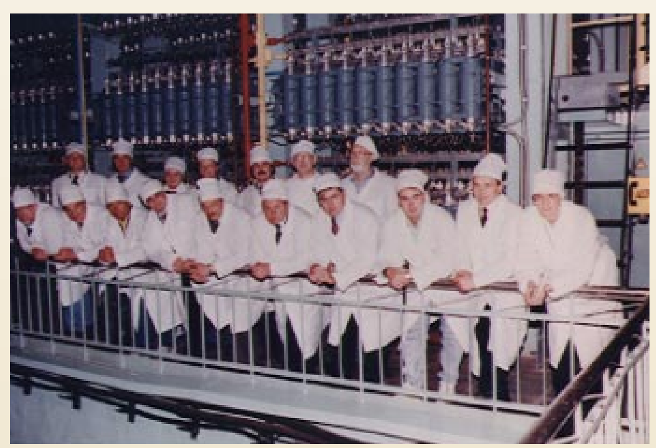
A major goal is to share expertise with the growing nuclear power industries in the Far East. Toward that end, Livermore is co-hosting a meeting in Las Vegas in September 1997 for industry representatives from South Korea, Taiwan, China, and Japan. The focus of the meeting, according to FESSP engineer Jor-Shan Choi, is repository issues and nuclear safety.

FESSP scientists are working with nations from the Former Soviet Union on two major projects. The first project is helping the NRC to provide the nuclear regulatory authority in Ukraine with information needed to establish regulatory control over radioactive wastes and spent nuclear reactor fuel. Ukraine, which formerly sent its wastes and spent fuel to Russia, must now build its own infrastructure.

The second effort is support to DOE in procuring highly enriched uranium obtained from dismantled Russian weapons. In 1994, Russia's Ministry of Atomic Energy agreed to dispose of 500 metric tons of Russian highly enriched uranium by converting it to low-enriched uranium and then selling it to the United States Enrichment Corporation (USEC). By the end of the 20-year contract, the weapons material from 20,000 Russian warheads will have been converted into enough fuel to generate an estimated 6 trillion kilowatt-hours of electricity, enough power to light the entire U.S. for about two years.

FESSP scientists and engineers are assisting DOE in developing and implementing so-called "transparency measures" to monitor the process that converts the highly enriched uranium to low-enriched fuel for nuclear power plants. The transparency measures, now in place at three Russian conversion facilities, ensure that the uranium comes from dismantled warheads. In exchange, the Russians will have periodic access to six U.S. power plants.

Finally, FESSP experts are aiding Livermore nonproliferation experts to enhance international safeguards for nuclear materials and to monitor reactor technology in developing countries.



Livermore provides technical expertise for implementing the transparency agreement under which the U.S. is purchasing low enriched uranium. Here, Scott McAllister (back row, left) and David Thomas (back row, second from right) are among a U.S. delegation and their Russian hosts, posing in front of centrifuges at Russia's largest uranium enrichment plant.

Figure 3. The FESSP simulates underground corrosion of rock storage materials for the proposed Yucca Mountain storage site. Livermore's new corrosion testing facilities are pictured here.

responsive to the needs of the NRC and DOE.

Chou says that another way the FESSP can make a significant contribution is to address the growing national consensus that a more integrated view of nuclear power is needed to effectively solve complex issues such as waste management. He notes that Tom Isaacs, head of Livermore's Policy, Planning, and Special Studies, is making a start on meeting that challenge. With FESSP help, he is working on a systematic approach for dealing with all issues related to nuclear materials use and management.

Chou also expects that the FESSP's partnerships with colleagues from other nations will continue to grow. Although the U.S. has no new nuclear power plants planned, other nations are building new plants at a very rapid rate. Japan, for example, has a vigorous nuclear power development program.

"Other countries turn to the U.S. for advice on nuclear safety," says Chou. "We can provide that advice. For our part, working with them helps the U.S. keep current with state-of-the-art nuclear technology."

The federal government has long relied on FESSP for scientific expertise, says Chou. "We're confident we'll continue to earn their trust."

— Arnie Heller

Key Words: Argus, FESSP, nuclear fuel cycle, nuclear power, Nuclear Regulatory Commission (NRC), nuclear safety, Nuclear Systems Safety Center (NSSC), nuclear waste, plutonium disposition, United States Enrichment Corporation (USEC), uranium enrichment, Yucca Mountain.

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About the Engineer

MARK STRAUCH came to Lawrence Livermore from the University of Michigan, where he received his B.S. and M.S. in electrical engineering in 1976 and 1978. An electrical engineer, he joined the Electronics Engineering Department to work on the Magnetic Fusion Energy Program. Since then, he has also supported the weapons program and O Division and was an Engineering group leader and division leader. He became deputy program leader of the Fission Energy and Systems Safety Program and assistant deputy associate director in the Energy Programs Directorate three years ago. Strauch is an active member of the Institute of Electrical and Electronics Engineers and currently is financial chair of the San Francisco Bay Area Council.

The Microtechnology Center

When Smaller Is Better

From thin-film windows to microactuators to photonic devices—the Center contributes to stockpile stewardship, bioscience, and nonproliferation projects at Livermore.

A dime-sized amplifier makes fiber-optic communications faster and clearer. A portable DNA analyzer helps detect and identify organisms in the field, including human remains and biological warfare agents. A tiny gripper inserted in a blood vessel treats aneurysms in the brain to ward off potential strokes. What do these technologies have in common? Each one is smaller than any comparable product, opening up a host of new applications. And each originated in Lawrence Livermore National Laboratory's Microtechnology Center.

In the late 1960s, Livermore scientists and engineers began making miniature devices for high-speed diagnostic equipment required for nuclear tests. For many years, before the development of Silicon Valley and the ready availability of microchips for a broad array of uses, Laboratory engineers fabricated chips to their own specifications for high-speed switches, high-speed integrated circuits, and radiation detectors. By the early 1980s, Livermore was fabricating thin-film membranes for use as x-ray windows in low-energy x-ray experiments, as x-ray filters, as debris shields for the Extreme Ultraviolet Lithography Program, and as targets for high-energy electron experiments in which x rays are generated.

These passive microstructures have been applied to dozens of projects. They have served as diagnostic devices for Livermore's Nova laser experiments and will do the same for experiments at the National Ignition Facility (NIF). Another microstructure, a novel thin-film window developed by Glenn Meyer and Dino Ciarlo, plays a critical role in a new, more efficient electron-beam system for